9B.8 DETERMINATION OF ALONG-WIND DIFFUSION FROM A QUASI-INSTANTANEOUS LINE SOURCE

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1. INTRODUCTION

Little data exist to characterize along-wind diffusion, especially for distances of more than a few kilometers. While there is a wealth of information on cross-wind and vertical diffusion, relatively few studies have been specifically designed to measure the along-wind diffusion parameter σ_x and how it varies with distance or atmospheric stability. This is due, in part, to a greater interest in continuous sources of industrial air pollution in which along-wind diffusion can be neglected. However, σ_x is an important parameter when considering instantaneous or quasi-instantaneous sources.

Accidental releases of toxic pollutants from stationary or mobile containment vessels can also pose an immediate threat to life and property. Many puff models apply the same expressions of cross-wind and vertical diffusion parameters, σ_y and σ_z, respectively, which are valid for continuous plumes, to an instantaneous release (Hanna 1996). Many transport and diffusion models commonly assume that σ_x and σ_y are the same. While these approaches may be useful as rough approximations for predicting downwind concentrations, they fail to recognize two fundamental problems. The diffusion coefficients σ_y and σ_z for an instantaneous puff are typically less than those for a continuous plume by a factor of two or more (Slade 1968). The magnitudes of σ_x and σ_y can vary greatly as functions of wind shear and convection. Pasquill (1974) notes that σ_x can be larger than σ_y due to the effects of wind shear. Short-range diffusion experiments and theoretical analyses indicate that $\sigma_x = \sigma_y$ is a poor assumption.

Most accidental releases of hazardous gases are usually a few minutes in duration simply due to the limit of the total available mass. The cloud is diffused by atmospheric eddies that are usually much larger than its width and expanded by eddies that are of comparable size. A cloud that is initially spherical in shape may be stretched by wind shear in the along-wind direction.

There are fundamental differences in dispersion between an instantaneous puff and a continuous plume. Hanna (1996) defines a length scale as $u_c T_d$, where u_c is the advective speed of the cloud and T_d is the source release duration. A release behaves more like an instantaneous puff when the dimensionless ratio $u_c T_d/\sigma_x << 1$ (Hanna 1996). Conversely, a release behaves more like a continuous plume when the $u_c T_d/\sigma_x >> 1$. Hanna et al. (1984) suggest that instantaneous dispersion parameters should be used either when the release time or sampling time is less than the transport time between the source and downwind receptor, while continuous dispersion parameters should be used when both the release and sampling times are greater than the transport time.

Direct measurement of puff dispersion using point samplers is difficult because the meandering component of the wind field sometimes carries puffs away from sampling arrays, and multiple releases are needed to build ensemble statistics. Ensemble statistics are not practical for puffs tracked over long distances because stability conditions within the boundary layer continuously change with time. Consequently, experimenters resort to the line source as an alternative means of obtaining σ_x information. However, the line source must be sufficiently long to simulate an "infinite" line so that the downwind samplers are not subjected to edge effects. There is also an assumption that the lateral mixing of material released along the line remains uniform. That is, variations in gas concentration within the line should be a function of along-wind and vertical mixing only (Fig. 1). In the absence of convection, the movement of a line source over a uniform surface should produce a reasonably uniform degree of vertical mixing. Thus, the passage of a uniform line source over an array of samplers oriented parallel to that line should produce concentration measurements that vary as σ_x varies along the line. If appropriate sampler spacing is used, each of these measurements can be taken as independent of the other for the creation of ensemble σ_x statistics.

The objective of the Over-Land Atmospheric Dispersion (OLAD) field experiment was to acquire a database on along-wind diffusion over 2 to 20 km for verification and improvement of the Vapor, Liquid and Solid Tracking (VLSTRACK) model and the Second-Order Closure Inte-

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grated Puff (SCIPUFF) dispersion model. A series of early and late morning trials at the Dugway Proving Ground (DPG) in September 1997 was conducted in which sulfur hexafloride (SF_6) was released by truck or airplane along a line approximately perpendicular to the mean wind. Lines of whole-air samplers and continuous analyzers were used to measure SF_6 concentrations downwind of the line source. Surface and upper-air meteorological measurements were also acquired.

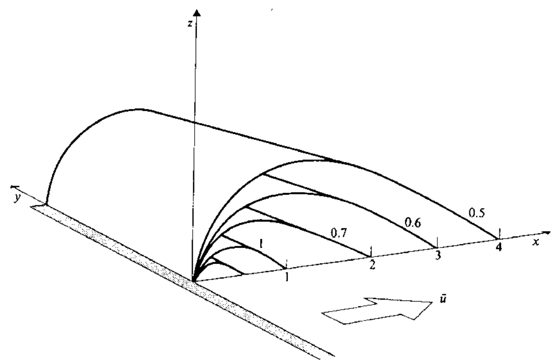

Fig 1. Theoretical cross-section of constant ambient concentration for an infinitely long line source along the y-axis. Only relative concentrations are indicated (from Williamson 1973).

2. SCIENTFIC BACKGROUND

There are several theoretical, empirical, and semi-empirical relationships that define σ_x as a function of time, distance, and/or atmospheric stability. However, there is little agreement about how σ_x varies with these parameters. Saffman (1962) and Chatwin (1968) used similarity theory to develop simple formulas for σ_x for an instantaneous cross-wind line source. Saffman (1962) found that $\sigma_x \sim t^{3/2}$ while Chatwin (1968) derived a relationship in which σ_x was a linear function of time. Csanady (1969) solved the diffusion equation based on the wind shear of an Ekman profile. His results showed that along-wind diffusion was a combination of turbulent and shear induced components. Accordingly, σ_x can be expressed as the quadratic sum of turbulent diffusion parameter σ_{xt} and a wind shear diffusion parameter σ_{xs} (Draxler 1979; Van Ulden 1992). Smith and Hay (1961) and Draxler (1979) present simple relationships for σ_{xt} which are proportional to time and the square of longitudinal turbulent intensity. Smith (1965) and Draxler (1979) give simple equations for σ_{xs} that are proportional to the wind shear. If a strong wind shear exists with very little vertical dispersion (i.e., stable boundary layer), the cloud tilts in the along-wind direction but there is little along-wind turbulent dispersion over the full depth of the cloud.

Several empirical expressions for σ_x have been developed based on short-range measurements. Through regression analysis, Drivas and Shair (1974) determined coefficients for $\sigma_x = at^b$, where the exponent b varied from 1.11 to 1.47. While they do not explicitly show how σ_x varies with stability, Drivas and Shair (1974) indicate that b is inversely proportional to the standard deviation of the horizontal wind direction σ_θ. Draxler (1979) determined a similar power-law relationship with b ranging from 1.1 to 1.3.

Several authors have attempted to develop stability-dependent expressions for σ_x. For example, Hansen (1979) developed a simple equation for σ_x as a function of Pasquill-Gifford stability. Wilson (1981) proposed a generalized analytical formula for σ_x for all stabilities assuming a logarithmic wind profile. Wilson (1981) points out that, except for very close to the source, along-wind diffusion tends to be dominated by vertical diffusion in combination with shear advection. Unfortunately, Wilson (1981) does not compare his parameterization of σ_x against field data. Dumbauld and Bowers (1983) proposed a simple, semi-empirical σ_x formula that included the effects of atmospheric turbulence and vertical wind shear. Van Ulden (1992) used Monin-Obukhov similarity theory to derive an analytical model that accounts for turbulence intensity and wind shear as well as for the effects of large horizontal eddies. For neutral conditions near the source, Van Ulden (1992) showed that his σ_x values are nearly the same as that given by Chatwin (1968).

3. EXPERIMENT DESCRIPTION

OLAD field trials were conducted at the DPG West Desert Test Range located near the southeast edge of the Great Salt Lake Desert about 125 km west-southwest of Salt Lake City, Utah. The test range terrain is relatively uniform with a slight southeast to northwest downward slope. Mountains border the test range to the east, west, and south. The area to the north is open to the Great Salt Lake Desert. The surrounding mountains, which rise about 700 m above the valley floor, create a channel for southeasterly and northwesterly winds. In the absence of moderate or strong synoptic forcing, solar heating creates northwesterly upslope winds. Strong radiational cooling at night generates southeasterly downslope winds.

A total of twelve lines of SF_6 were released perpendicular to the mean wind over ten separate days (Table 1). A truck was used to release SF_6 over a 10-km line near the surface. An airplane was used to disseminate SF_6 over an 18-km line at an altitude of 100 m. SF_6 line source characteristics are listed in Table 2.

Three sampling lines parallel and downwind to the SF_6 release line were deployed for each trial. Each sampling line consisted of fifteen sequential whole-air samplers spaced 100 m apart. Each sampler contained twelve one-liter bags that were sequentially filled over 15-min increments. Scientech TGA-4000 fast response continuous analyzers were positioned at the ends of each sampling line. SF_6 concentration data were acquired at a rate of 4 Hz by the continuous analyzers.

An aggressive quality assurance and quality control program was implemented for the SF_6 monitoring component of OLAD. The whole-air samplers filled a total of 4,236 bags. Instrument failures, incorrectly handled cartridges, and analytical errors invalidated 780 samples for a data recovery rate of 82%. The accuracy and precision of the sampling method were determined using dynamic blanks, dynamic spikes, and duplicate samples. Watson et al. (1998) describes details of the sampling methodology.

Table 1. OLAD Test Summary

Date	Release Type	Release Time (MDT)	Mixing Height (m)	PG Class
08 SEP 97	Ground	07:05	200	F
09 SEP 97	Ground	06:45	300	E
10 SEP 97	Air	07:29	400	F
11 SEP 97	Air	06:56	200	F
12 SEP 97	Ground	06:57	300	F
15 SEP 97	Ground	06:44	200	D
	Ground	07:54	700	D
	Ground	08:38	700	D
17 SEP 97	Air	06:48	200	F
18 SEP 97	Ground	07:55	200	D
24 SEP 97	Air	07:09	200	F
25 SEP 97	Ground	04:00	200	F

Eight meteorological monitoring stations were deployed over the test range. R. M. Young wind monitors at 2 m above the surface acquired surface winds. A Campbell Scientific CS500 probe acquired air temperature and relative humidity. Wind profiles were acquired by optically tracked 30-g pibals. An AIR automatic radiotheodolite was used to track rawinsondes that obtained profiles of air temperature, relative humidity, and wind velocity.

Table 2. Test Characteristics

	Ground	Air
Line Distance (km)	10	18
Mass of SF_6 (kg)	10	100
Release Rate (kg s^{-1})	0.025	0.550
Release Time (s)	400	180
Vehicle Velocity (m s^{-1})	25	100
Line 1 Downwind Distance (m)	1616	9562
Line 2 Downwind Distance (m)	4024	15980
Line 3 Downwind Distance (m)	8859	20800

4. ANALYSIS

Data acquired by the whole-air samplers were used to test the line uniformity assumption. Substantial variance in SF_6 concentration was observed along the sampling line closest to the release line. For example, during the 12 September test, the line 1 mean value of the SF_6 concentration peak had a standard deviation of about 60% (Table 3). Farther downwind on line 2, the standard deviations ranged from 10 to 50% of the mean value for peak concentrations. For line 3, the standard deviations were only 20 to 30% of the mean. In general, SF_6 concentrations displayed the greatest variance for the closest sampling line and generally decreased in magnitude with increasing distance from the release line. It must be pointed out that the absolute concentrations of SF_6 are at least an order of magnitude smaller for line 3 than for line 1. This, of course, is due to increased mixing of the cloud with distance. At the 95% confidence limit, SF_6 concentrations between duplicate samplers agreed to within 20%. Thus, the variations in mean concentrations between samplers along each line are statistically significant. SF_6 concentrations from airplane releases showed much less variability than the ground releases. However, the variability observed along the sampling lines was larger than that found in duplicate samplers. These analyses show that the uniform line source assumption is not valid, at least for individual test cases during very stable atmospheric conditions over land.

Table 3. 12 September 1997 SF_6 Statistics

Time	Line 1		Line 2		Line 3	
(MDT)	Mean	Std.	Mean	Std.	Mean	Std.
07:00	12	16	5	1	5	1
07:15	69	79	5	1	5	1
07:30	7543	4849	13	18	6	6
07:45	6100	3302	1937	1034	7	10
08:00	58	50	5128	560	5	1
08:15	81	151	2935	957	23	15
08:30	32	20	231	160	78	23
08:45	63	111	34	13	176	37
09:00	47	67	19	6	307	79
09:15	204	456	13	3	333	72
09:30	60	77	42	38	207	57
09:45	69	97	147	39	49	46

Gaussian curves were fitted to time series of SF_6 concentration data acquired by each of the continuous analyzers. These fits were used to derive σ_x and the speed of the SF_6 cloud. In general, most of the Gaussian fits were quite good. Figure 2 is an example of a time series of SF_6 concentration acquired on the first sampling line during the 12 September test. The best-fit Gaussian curve is also shown as a dashed line. All of the derived values of σ_x from all tests are shown as a function of downwind distance in Figure 3. The power-law regression fit shows a good correlation coefficient of 0.87. However, no apparent correlation exists between σ_x and atmospheric stability. The SF_6 cloud speed was found to be approximately 1.7 times that of the surface scalar wind speed with a correlation coefficient of 0.94. This suggests that there must be some limited vertical mixing of the SF_6 cloud to levels where stronger winds exist. Many of the wind profiles acquired by pibals and rawinsondes clearly show distinct wind shear between the surface and 100 m.

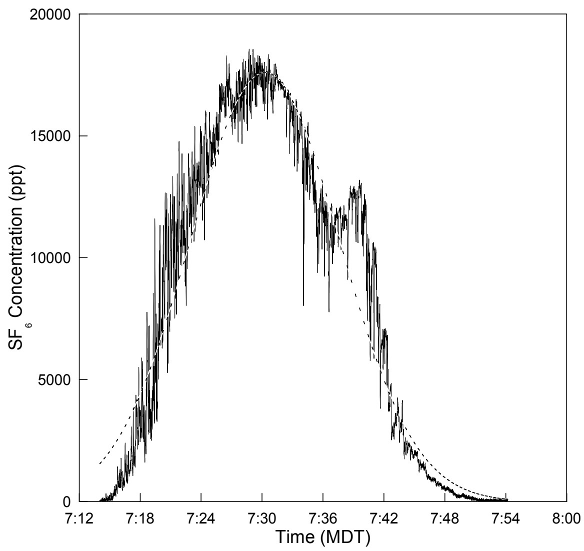

Fig. 2. SF_6 time series from a continuous analyzer located on line 1 during 12 September test.

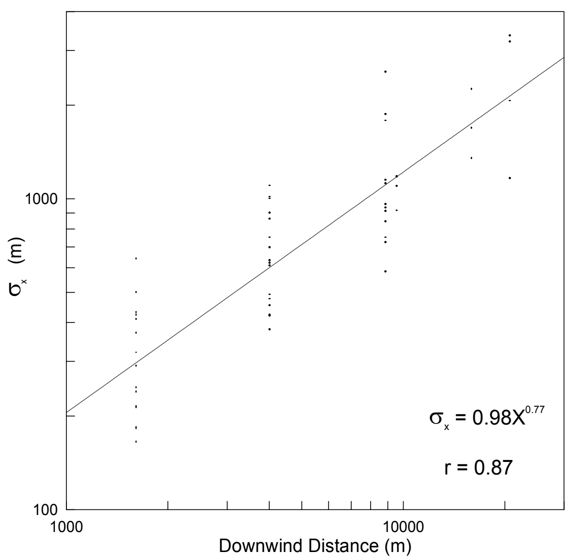

Fig 3. Along-wind diffusion coefficient as a function of downwind distance for all cases.

5. CONCLUSIONS

The uniform line source assumption is not valid for individual SF_6 releases during stable atmospheric conditions over land. Significant variability in downwind SF_6 concentration was found along each sampling line. An empirical dependence of σ_x as a function of downwind distance was found. However, no apparent relationship was found between σ_x and atmospheric stability.

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